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COMPLEMENTARY PRODUCTS AND DEVICES

ORDER OF SELECTION AND DESIGN OF MAGNETIC CLUTCHES FOR SEALED MACHINES

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A technique for selection and design of magnetic clutches with highly coercive permanent magnets (barium oxide magnets or magnets produced from such alloys of rare-earth elements as samarium–cobalt and neodymium–iron–boron) for sealed machines (pumps, compressors, mixers) is presented.

Magnetic clutches are intended for contact-free transmission of rotary motion across a fixed partition through the interaction forces of permanent magnets. With the use of highly coercive barium-oxide magnets and magnets produced from rare-earth alloys (samarium–cobalt, neodymium–iron–boron), it becomes possible to decrease the overall dimensions of magnetic clutches (Figs. 1, 2). Magnetic clutches are used in sealed machines in dangerous industries. The design of such machines and apparatuses is a difficult procedure in view of the absence of criteria for the selection of magnetic clutches according to basic parameters. The objective of the present article is to develop a technique for selecting and designing magnetic clutches with highly coercive permanent magnets produced from barium oxide and rare-earth alloys.

Initial data in the selection and design of magnetic clutches: kinematic circuit of machine; clutch ratio of drive and driven elements of machine; nominal rotational speed of asynchronous electric motor; characteristic of load moment on working unit as a function of rotational speed; mechanical characteristic of asynchronous electric motor constructed from reference data; reduced moments of inertia of rotation for drive and for driven parts of machine; requirements imposed on construction materials and characteristics of working medium; gauge or vacuum-gauge pressure in working cavity of machine or apparatus.

Determination of Geometric Dimensions of Clutch with Tight Packing of Barium-Oxide Magnets [1]

1. It is recommended that the length l_m of the magnets (Figs. 3, 4) be set equal to 10–12 mm with gaps between the drive and driven half-clutches $\delta < 4$ mm and equal to 15–16 mm with $\delta > 4$ mm.

2. The gap δ is selected on the basis of the thicknesses Δ_1 and Δ_2 of the protective shells of the half-clutches, the thickness δ_s of the wall of the airtight shield and the assured air gap between the wall of the shield and the protective shells (at least 0.5 mm).

3. The maximum value of the coefficient K_0 for a given gap and a value of the dimensionless coefficient q_0 that assures the greatest torque of the magnetic clutch corresponding to K_0 are selected (Table 1).

4. The width τ of the band of the magnet (not final, since an even number of magnet poles is determined), m: $\tau = 2\delta/q_0$, where δ is the gap between the half-clutches relative to the magnets, m, is selected.

5. The maximum torque of the magnetic clutch is specified (at the present stage, it is set equal to the maximum moment of the asynchronous electric motor).

6. The following are determined: for a *cylindrical clutch*, the outer diameter of the internal half-clutch,

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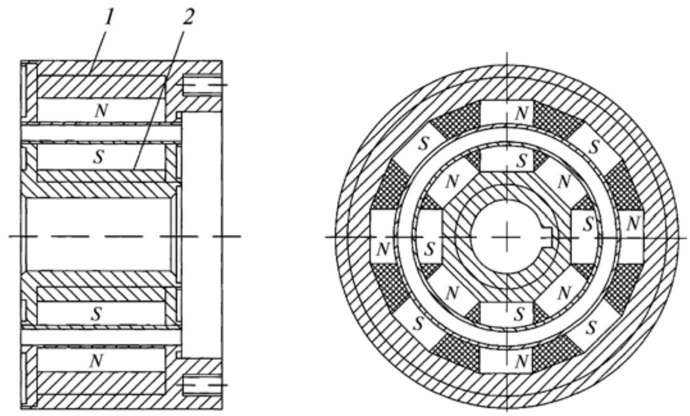

Fig. 1. Cylindrical magnetic clutch: *1*, *2*) external and internal half-clutches.

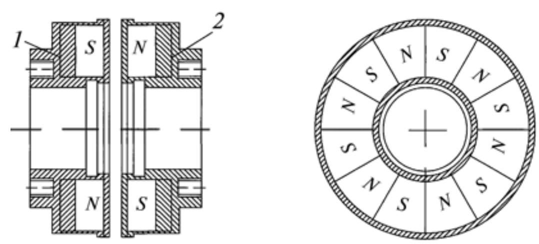

Fig. 2. Front magnetic clutch: *1*, *2*) half-clutches.

$$D_i = \sqrt{M_{\max} / 0.125 \propto_0 K_0 l J^2}\text{, m;}$$

for a *front clutch*, the outer diameter of the magnets,

$$D = \sqrt[3]{M_{\max} / 0.0175 \propto_0 K_0 J^2}\text{, m,}$$

where $M_{\max}$ is the maximum torque of the magnetic clutch, N·m; $\propto_0 = 4\pi \cdot 10^{-7}$ H/m, magnetic constant; K_0, a dimensionless coefficient that depends on the air gap between the half-clutches and the ratio of the air gap to the width of the pole; l, active length of magnet along axis of rotation, m; J, magnetization of magnets, A/m. For 16BA190 magnets, it is recommended that J = 220,000 A/m, while for 25BA150 magnets, it is recommended that J = 240,000 A/m (State Standard GOST24063). In designing cylindrical clutches, the value of l or D_i is specified on the basis of structural consideration. The inner diameter of the magnets for front clutches is set equal to one-half the computed diameter of the clutch.

7. The thickness of the magnetic circuit is calculated: $\delta_m = 0.5 l_m$.

8. The number of poles in the clutch is determined: for cylindrical clutches, $N = \pi D_i / \tau$; for front clutches, $N = 3\pi D / 4\tau$. The computed value of N is rounded to the nearest even number after which the quantities τ, q_0, K_0, and $M_{\max}$ are redetermined.

9. The moments of inertia of the half-clutches and the reduced moments of inertia of the drive and driven components are calculated.

Determination of Geometric Dimensions of Cylindrical Clutches with Tight Packing of Rare-Earth Magnets [2, 3]

1. It is recommended that the length of the magnets l_m (cf. Figs. 3, 4) or h and H (Fig. 5) be set equal to 8–10 mm with gaps between the drive and driven half-clutches δ = 5–7 mm.

TABLE 1

Gap δ, mm	Values of q_0							
	0.20	0.25	0.30	0.40	0.50	0.60	0.80	1.0
	Values of K_0							
3	2.76	2.28	2.65	2.40	2.12	1.99	1.60	1.32
4	2.62	2.66	2.61	2.36	2.06	1.91	1.56	1.29
5	2.28	2.36	2.44	2.33	2.04	1.76	1.52	1.27
6	2.08	2.20	2.30	2.28	2.01	1.65	1.48	1.26
8	1.54	1.61	1.69	1.97	1.86	1.59	1.42	1.23
10	1.14	1.20	1.36	1.46	1.65	1.55	1.28	1.14
12	0.96	0.99	1.02	1.12	1.28	1.28	1.17	1.06
14	0.82	0.85	0.88	0.96	1.01	1.14	1.09	1.01
16	0.74	0.78	0.84	0.89	0.95	0.98	0.98	0.92
20	0.62	0.67	0.71	0.74	0.79	0.81	0.81	0.76

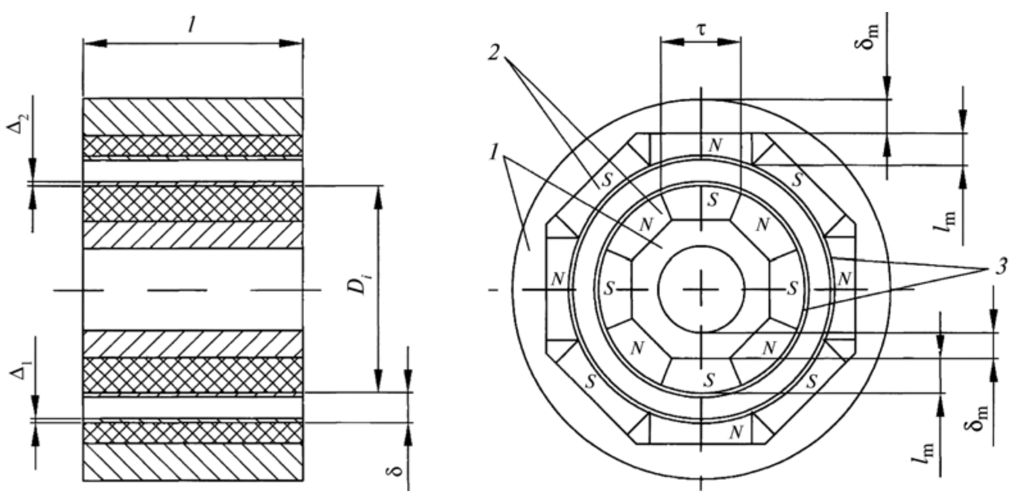

Fig. 3. Basic dimensions of a cylindrical magnetic clutch: *1*) magnetic circuit; *2*) magnet; *3*) protective shell.

2. The gap δ is selected on the basis of the thicknesses Δ_1 and Δ_2 of the protective shells of the half-clutches, the thickness δ_s of the wall of the airtight shield, and the assured air gap between the wall of the shield and the protective shells (at least 0.5 mm).

3. The dimensions D_i and l (B, b) are specified on the basis of structural considerations.

4. The optimal number N of poles as a function of the dimension D_i is determined (the nearest smaller even number of poles is adopted) (Fig. 6).

5. The width a of a pole of a magnet with respect to the outer diameter of the magnets of the internal half-clutch $a = (D_i - 2h)\sin\varphi$, where $\varphi = \pi/n$ and $D_i = 2r$, is determined.

6. The width of a pole of a magnet of the external half-clutch $A = (D_i + 2\delta)\sin\varphi$. The dimensions A and a are rounded to the next smaller integral values.

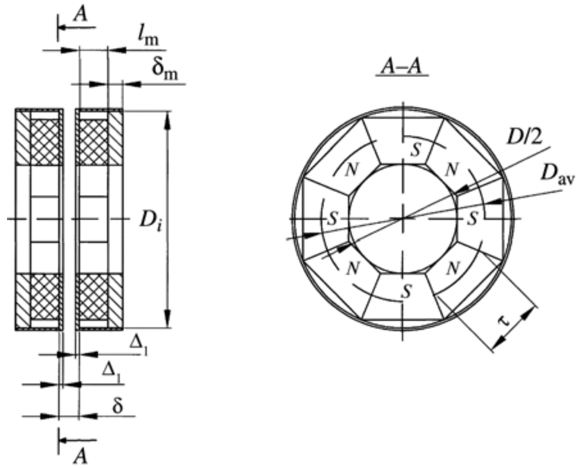

Fig. 4. Basic dimensions of front magnetic clutch.

TABLE 2

j	s_j	t_j	u_j
1	$(2x + a)\cos\varphi + A - 2z\sin\varphi$	$2y + b + B$	$(2x + a)\sin\varphi + 2z\cos\varphi$
2	$(2x - a)\cos\varphi - A - 2z\sin\varphi$	$2y + b + B$	$(2x - a)\sin\varphi + 2z\cos\varphi$
3	$(2x - a)\cos\varphi + A - 2z\sin\varphi$	$2y + b - B$	$(2x - a)\sin\varphi + 2z\cos\varphi$
4	$(2x + a)\cos\varphi - A - 2z\sin\varphi$	$2y + b - B$	$(2x + a)\sin\varphi + 2z\cos\varphi$
5	$(2x - a)\cos\varphi + A - 2z\sin\varphi$	$2y - b + B$	$(2x - a)\sin\varphi + 2z\cos\varphi$
6	$(2x + a)\cos\varphi - A - 2z\sin\varphi$	$2y - b + B$	$(2x + a)\sin\varphi + 2z\cos\varphi$
7	$(2x + a)\cos\varphi + A - 2z\sin\varphi$	$2y - b - B$	$(2x + a)\sin\varphi + 2z\cos\varphi$
8	$(2x - a)\cos\varphi - A - 2z\sin\varphi$	$2y - b - B$	$(2x - a)\sin\varphi + 2z\cos\varphi$
9	$-(2x + a)\cos\varphi + A + 2z\sin\varphi$	$-2y + b + B$	$-(2x + a)\sin\varphi - 2z\cos\varphi$
10	$-(2x - a)\cos\varphi - A + 2z\sin\varphi$	$-2y + b + B$	$-(2x - a)\sin\varphi - 2z\cos\varphi$
11	$-(2x - a)\cos\varphi + A + 2z\sin\varphi$	$-2y + b - B$	$-(2x - a)\sin\varphi - 2z\cos\varphi$
12	$-(2x + a)\cos\varphi - A + 2z\sin\varphi$	$-2y + b - B$	$-(2x + a)\sin\varphi - 2z\cos\varphi$
13	$-(2x - a)\cos\varphi + A + 2z\sin\varphi$	$-2y - b + B$	$-(2x - a)\sin\varphi - 2z\cos\varphi$
14	$-(2x + a)\cos\varphi - A + 2z\sin\varphi$	$-2y - b + B$	$-(2x + a)\sin\varphi - 2z\cos\varphi$
15	$-(2x + a)\cos\varphi + A + 2z\sin\varphi$	$-2y - b - B$	$-(2x + a)\sin\varphi - 2z\cos\varphi$
16	$-(2x - a)\cos\varphi - A + 2z\sin\varphi$	$-2y - b - B$	$-(2x - a)\sin\varphi - 2z\cos\varphi$

7. The force of attraction of the two magnets and the maximum torque of the clutch are determined:

$$f_{x1} = \frac{\propto_0 J^2}{n_0 \pi} \sum_{j=1}^{16} \left[t_j u_j \arctan\left(\frac{s_j t_j}{u_j q_j}\right) - s_j t_j \operatorname{artanh}\left(\frac{t_j}{q_j}\right) - \frac{1}{2}(t_j^2 - u_j^2) \operatorname{artanh}\left(\frac{s_j}{q_j}\right) + \frac{1}{2} s_j q_j \right], \quad (1)$$

where s_j, t_j, and u_j are variables (Table 2); $q_j = (s_j^2 + t_j^2 + u_j^2)^{1/2}$; $n_0 = 16$; $M_{max} = Nm(x, z)$ (x and z are the coordinates of the magnet),

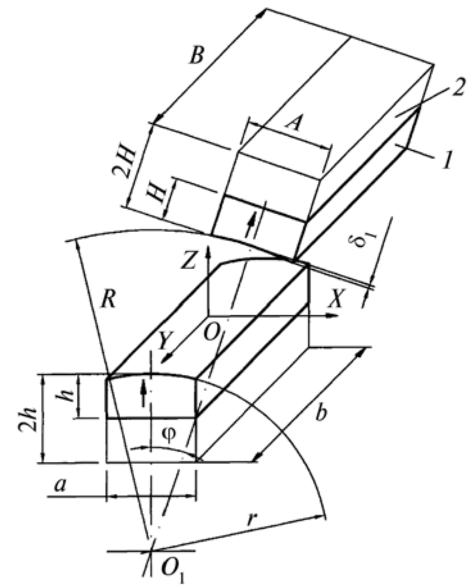

Fig. 5. Relative position of magnets in space with rotation of external half-clutch relative to internal half-clutch by an angle φ: *1*) magnet; *2*) magnetic circuit; *O* – center of lower magnet; *X*, *Y*, *Z* – coordinate axes; $A \cdot B \cdot H$ and $a \cdot b \cdot h$ – dimensions of upper and lower magnets, respectively; δ_1 – depth of polishing of magnet.

$$m(x, z) = \left[f_{x1}(x, z) - f_{x1}(x + 2H\sin\varphi, z + 2H\cos\varphi)\right]D_i/2 -$$

$$-\left[f_{x1}(x, z + 2h) - f_{x1}(x + 2H\sin\varphi, z + 2h + 2H\cos\varphi)\right](0.5D_i - 2h). \quad (2)$$

The coordinates of the magnet of the (polished) external half-clutch are as follows:

$$\left.\begin{aligned} x &= (D_i + 2\delta - 2\delta_1)/2\sin\varphi; \\ z &= (D_i + 2\delta - 2\delta_1)/2\cos\varphi - D_i/2. \end{aligned}\right\} \quad (3)$$

It is recommended that the magnetization J be set equal to 612,000 A/m for KS-37 magnets (specifications TU 48-4-411-78 and TU 48-4-415-79, Sm–Co alloy, first group) and to 636,000 A/m for KS-25DTs magnets (TU-48-4/0531-6-92, Sm–Co alloy, first group) and Ch36R magnets (TU 6391-002-55177547-2005, Nd–Fe–B alloy, second group). The magnets are manufactured at POZ-PROGRESS (Verkhnyaya Pyshma, Sverdlovsk Oblast). If magnets of other groups with higher magnetization are used, it is recommended that the magnetization of the magnets $J = J_r$, where $J_r = B_r/\propto_0$ is the residual magnetization, A/m, and B_r the residual induction of the magnet, T.

8. The thickness of the magnetic circuit $\delta_m = h$ for an internal half-clutch and $\delta_m = H$ for an external half-clutch.

9. The value of the maximum moment of the clutch at this stage of design must be close to the maximum moment of the electric motor. This is achieved through selection of the dimension l (B, b).

10. The moments of inertia of the half-clutch and the reduced moments of inertia of the drive and driven parts are calculated.

Determination of Geometric Dimensions of Cylindrical Clutch with Rare-Earth Magnets of Identical Dimensions in the External and Internal Half-Clutches ($A = a$, $B = b = l$, $H = h = l_m$)

Rare-earth magnets are manufactured in widths A = 10, 12, 15, 18, 20, 25, and 30 mm. It is recommended that magnets of width 15, 18, 20, and 25 mm be used. The use of narrower magnets (A = 10 or 12 mm) represents a time-consuming process. The use of wide magnets (A = 30 mm) leads to significant losses of expensive material in the course of polishing of

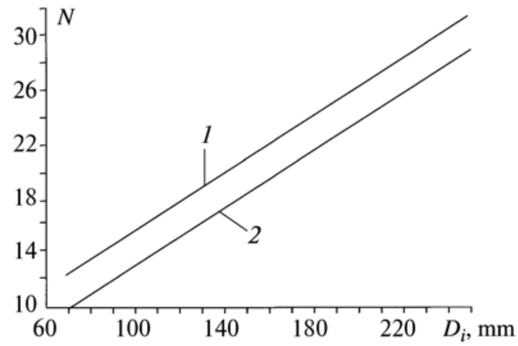

Fig. 6. Optimal number of poles in magnetic clutch with rare-earth magnets with gap δ: *1*) 5 mm; *2*) 7 mm.

TABLE 3

f	s_f	t_f	u_f
1	$(2x + a)\cos\varphi + a - 2z\sin\varphi$	$2y + 2b$	$(2x + a)\sin\varphi + 2z\cos\varphi$
2	$(2x - a)\cos\varphi - a - 2z\sin\varphi$	$2y + 2b$	$(2x - a)\sin\varphi + 2z\cos\varphi$
3	$(2x + a)\cos\varphi - a - 2z\sin\varphi$	$2y$	$(2x + a)\sin\varphi + 2z\cos\varphi$
4	$(2x - a)\cos\varphi + a - 2z\sin\varphi$	$2y$	$(2x - a)\sin\varphi + 2z\cos\varphi$
5	$-(2x + a)\cos\varphi + a + 2z\sin\varphi$	$-2y + 2b$	$-(2x + a)\sin\varphi - 2z\cos\varphi$
6	$-(2x - a)\cos\varphi - a + 2z\sin\varphi$	$-2y + 2b$	$-(2x - a)\sin\varphi - 2z\cos\varphi$
7	$-(2x + a)\cos\varphi - a + 2z\sin\varphi$	$-2y$	$-(2x + a)\sin\varphi - 2z\cos\varphi$
8	$-(2x - a)\cos\varphi + a + 2z\sin\varphi$	$-2y$	$-(2x - a)\sin\varphi - 2z\cos\varphi$

the outer and inner diameters of the half-clutches beneath the protective shells. A clutch of required length l in the axial direction is assembled from several standard magnets.

1. A standard length of magnets is recommended: l_m (H, h) = 8 mm with gaps δ = 3–5 mm; l_m = 10 mm with δ = = 5–10 mm; and l_m = 15 mm with $\delta > 10$ mm.

2. The gap δ is selected on the basis of the thicknesses Δ_1 and Δ_2 of the protective shells of the half-clutches, the thickness δ_s of the wall of the airtight shield, and the assured air gap between the wall of the shield and the protective shells (at least 0.5 mm).

3. The dimensions D_i and l (B, b) are specified on the basis of structural considerations.

4. The standard width of the magnet A (a) and length l_m (H, h) are selected.

5. The number of poles in the clutch is determined: $N = (D_i - 2h)\pi/a$. The computed value of N is rounded to the nearest smaller even number.

6. The maximum turning angle of the half-clutches (geometric) $\varphi = \arctan(a/(D_i - 2h))$ is determined.

7. The force of attraction of two magnets is determined on the basis of (1) (where the variables s_f, t_f, and u_f (Table 3) are substituted in place of the variables s_j, t_j, and u_j): $q_f = (s_f^2 + t_f^2 + u_f^2)^{1/2}$; $n_0 = 8$.

The maximum torque of the clutch $M_{max} = Nm'(x, z)$, where $m'(x, z)$ is calculated from (2).

The coordinates of the magnet of the (polished) external half-clutch are determined from (3).

8. The thickness of the magnetic circuit $\delta_m = h$ for an internal and external half-clutch.

TABLE 4

τ_r	2	3	4	5	6	8	10
β_e	0.42	0.52	0.61	0.66	0.70	0.76	0.80

TABLE 5

Brand of magnet	16BA190	25BA150	KS-37	KS-25DTs	Ch36R
B_r, T	0.30–0.35	0.35–0.40	0.77–0.90	0.82–1.07	0.60–1.22

9. At the present stage, the value of the maximum moment of the clutch must be close to the maximum moment of the electric motor. This is achieved by selection of the dimension l (B, b).

10. The moments of inertia of the half-clutches and the reduced moments of inertia of the drive and driven parts are calculated.

Determination of Losses in Shield and Degree of Heating of Shield [4, 5]

1. Losses are determined only for shields manufactured from nonmagnetic conducting materials with high specific electric resistance.

2. The values of the relative pole pitch are determined: for a front clutch, $\tau_r = 3\pi D/4N\delta$; for a cylindrical clutch, $\tau_r = \pi(D_i + \delta)/N\delta$.

3. A dimensionless coefficient β_e of the effective induction in the clutch gap is selected on the basis of the relative pole pitch τ_r of the magnetic clutch (Table 4).

For intermediate values of τ_r, the coefficient β_e is determined by the method of interpolation.

4. The value of the effective induction in the gap $B_e = \beta_e K_J B_r$, where $K_J = 0.90$–0.95 is a dimensionless coefficient that takes into account the decrease in the magnetization of a magnet in the clutch and B_r the residual induction of the material of a permanent magnet, T (Table 5).

5. Losses of power P_s in the conducting shield, W, are determined: for front clutches, $P_s = 3.3B_e^2 D^4 n^2 \delta_s/\rho$; for cylindrical clutches, $P_s = 31B_e^2 D_s^3 n^2 l \delta_s/\rho$, where D_s is the outer diameter of the shield of the cylindrical clutch, m; n, rotational speed of clutch, sec^{-1}; δ_s, thickness of wall of shield, m; and ρ, specific resistance of material of shield, Ω·m.

6. The coefficient of convective heat transfer K_{ct} from the surface of the shield in natural air cooling, W/(m^2·sec), is determined: for front clutches, $K_{ct} = 14 + 0.005P_s/\pi D^2$; for cylindrical clutches, $K_{ct} = 14 + 0.0013P_s/\pi D_s l$.

7. The temperature difference $\Delta\theta$ between the shield and the environment, °C, is determined: for front clutches, $\Delta\theta = 2P_s/\pi D^2 K_{ct}$; for cylindrical clutches, $\Delta\theta = 2P_s/2\pi D_s l K_{ct}$. If the quantity $\Delta\theta$ is greater than 80°C, forced air or water cooling of the shield is necessary.

8. The flow rate Q_l of the cooling liquid in air cooling of the shield, m^3/sec, is determined:

$$Q_l = P_s \cdot 10^{-3}/\Delta\theta_1 c,$$

where $\Delta\theta_1$ is the permissible temperature difference between the shield and the cooling liquid, °C (not less than 20°C), and c is the specific heat capacity of the cooling liquid, J/(kg·°C) (for water, $c = 4.19 \cdot 10^3$ J/(kg·°C)).

9. As the temperature increases, the magnetization of the permanent magnets and the torque of the magnetic clutch both decrease; the latter is determined at the working temperature:

$$M_t = M_{max}(1 - \alpha t_w)^2/(1 - \alpha t_n)^2,$$

where M_t and M_{max} are, respectively, the torque at the working temperature and at the normal temperature, N·m; t_w, $t_n = 20$°C, respectively, working and normal temperature, °C; α, temperature coefficient of magnetization (magnetic induction), 1/°C.

TABLE 6

t_w, °C		60	80	100	120	140	160	180	200	250	300	350	400
M_t/M_{max}	16BA190, 25BA150	0.84	0.77	0.69	0.63	0.56	0.50	0.44	0.39	0.27	0.17	–	–
	KS-37	0.97	0.95	0.93	0.91	0.89	0.87	–	–	–	–	–	–
	KS-25DTs	0.98	0.96	0.95	0.93	0.92	0.90	0.89	0.87	0.74	0.69	0.64	0.59
	Ch36R	0.93	0.90	0.87	0.84	–	–	–	–	–	–	–	–

For magnetic clutches with 16BA190 and 25BA150 magnets, $\alpha = 0.002$ 1/°C; for magnetic clutches with KS-37 magnets, $\alpha = 0.0005$ 1/°C; and for magnetic clutches with KS-25DTs magnets, $\alpha = 0.0004$ 1/°C (with $t_w > 200$°C, $\alpha = 0.0006$ 1/°C); and with Ch36R magnets, $\alpha = 0.0008$ 1/°C (class of magnet B).

Table 6 presents the magnitudes of the ratio of moments M_t/M_{max} as a function of temperature [6].

Dynamic Calculation

1. The torque of the shield $M_s = 0.159P_s = n$ is determined.

2. The maximum error angle of the half-clutches in the start-up period of a machine with an asynchronous motor, rad, is determined:

under a constant load,

$$(\alpha_1 - \alpha_2)_{max} = \frac{0.85}{(I_1/I_2)^{0.6}(M_t/M_{max.em})^{1.2}} + 0.125\frac{M_s}{M_{nom}} + \frac{1.7M_l}{M_t};$$

under a ventilator load,

$$(\alpha_1 - \alpha_2)_{max} = \frac{0,85}{(I_1/I_2)^{0.6}(M_t/M_{max.em})^{1.2}} + 0.125\frac{M_s}{M_{nom}} + \frac{0.27M_l}{M_{nom}(1.2)^{L'}},$$

where $L' = M_t/M_{nom}$; I_1 and I_2, reduced moments of inertia of masses of drive and driven parts, kg·m^2; M_{nom} and $M_{max.em}$, nominal and maximum moments of asynchronous electric motor, N·m; M_s, torque of shield, N·m; M_l, load moment, N·m.

The value of the maximum error angle of the half-clutches must not exceed 0.5π. If $(\alpha_1 - \alpha_2)_{max} > 0.5\pi$, it is necessary to increase the dimensions D, D_i, and l and to repeat the calculation. The optimal error angle of the half-clutches (at which the machine functions stably and the dimensions of the magnetic clutch are least) is in the range (0.35–0.5)π rad (electrical).

3. The eigen frequency f_{ef} of the magnetic clutch, Hz, is determined.

$$f_{ef} = \frac{1}{2\pi}\sqrt{\frac{(I_1 + I_2)NM_t \sin(\alpha_1 - \alpha_2)_{max}}{2I_1I_2(\alpha_1 - \alpha_2)_{max}}}.$$

Disruption of the magnetic coupling of the half-clutches as a consequence of resonance phenomena is possible with close values of f_{ef} and the forced oscillation frequency of the drive.

4. The excursion time t_{exc} of a machine with asynchronous motor, sec, is determined:

$$t_{exc} = 2(I_1 + I_2)\omega_n\left(\frac{1 - S_c}{M_{max.em} + M_{min.em}} + \frac{S_c}{M_{max.em} - M_{nom}}\right),$$

where ω_n is the angular speed of the electric motor (nominal), rad/sec; S_c, critical slip of asynchronous electric motor; $M_{min.em}$, minimal moment of asynchronous electric motor, N·m.

5. The force of attraction F between the half-clutches of a front clutch, N, is determined:

$$F = 0.28\propto_0 J^2\left(\sqrt{4+(8\delta/D)^2} - \frac{8\delta}{D}\right)S_{m1}e^{-3.3\nu},$$

where $\nu = \delta/\tau$, and S_{m1} is the area of the poles of the front magnetic half-clutch, m^2.

On the basis of theoretical and experimental studies, a technique was developed for selecting magnetic clutches for sealed machines. The technique was tested on actual machines that had been introduced into the production process. The computation error of the basic parameters of the magnetic clutches with 0.95 confidence level does not exceed 15%.

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